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Rising Total Hadron-Hadron Cross Sections

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In honour of George T. Zatsepin

Abstract. A historical summary is made on the measurements concerning the rising total hadron-hadron cross sections at high energies. The first part of this paper concerns the total cross section measurements performed at the Brookhaven, Serpukhov and Fermilab fixed target accelerators; then the measurements at the CERN Intersecting Storage Rings (ISR), and at the CERN and at the Tevatron Fermilab $\bar{p}p$ colliders; finally the cosmic ray measurements at even higher energies. A short discussion on Conclusions and Perspectives follows.

1 Introduction

Hadron-hadron total cross sections were accurately measured at most new hadron accelerators which opened up new energy regions. Most of the systematic total cross section measurements of the 6 long-lived charged hadrons ($\pi^{\pm}, K^{\pm}, p^{\pm}$) on hydrogen and deuterium targets at fixed target accelerators were performed using the transmission method, pioneered in the 1960's at Brookhaven National Laboratory (BNL); the method is capable of high precisions, typically point to point precisions of $\sim$0.2% and a systematic scale uncertainty of <1.0%.

Fig. 1, from the Data Particle Group, shows the behaviour with energy of the total cross sections of $\pi^{\pm}p$, $\pi^{\pm}d$. At low energies, in the so called *resonance region*, one observes a number of peaks and structures which decrease in size as the energy increases. Above 5 GeV/c lab momentum, in the *continuum region*, there are no more structures: the cross sections decrease smoothly, reach a minimum and then slowly rise with increasing energy (the *asymptotic region*). In the low energy region the cross sections depend strongly on the type of colliding hadrons and on the total isotopic spin, while at high energies these dependences tend to disappear as the energy increases.

The BNL experiments in the 1960's concerned the resonance region and the beginning of the continuum region. The experiments performed later at the then new Serpukhov accelerator by the CERN-Serpukhov collaboration in the early 1970's discovered the flattening of the K^{-}p total cross sections (1970) and the rising K^{+}p total cross sections (1971). Then followed the experiments at the CERN ISR pp collider, where it was found that the pp total cross section was also rising (1973). Later in the 1970's systematic measurements were made at the new Fermilab Tevatron fixed target accelerator using the BNL-Serpukhov method: it was found that also the $\pi^{\pm}$p and K^{-}p total cross sections were rising with increasing energy. One had to wait for the CERN and Tevatron $\bar{p}p$ colliders to prove that also the $\bar{p}p$ total cross section was rising.

The highest energies were and are still available only in cosmic rays: cosmic ray (CR) measurements indicate in 1972 that the pp total cross section was rising as the energy increased.

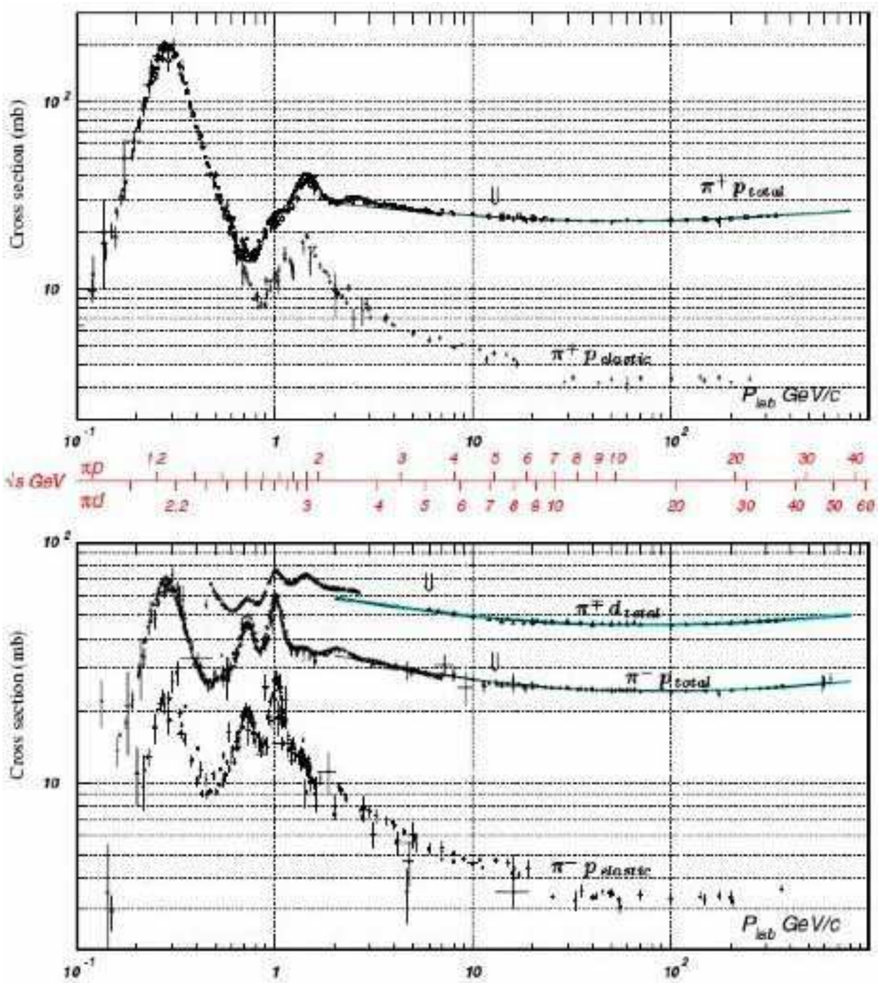

Figure 1: Compilations of the total and of the integrated elastic cross section data versus lab momentum for $\pi^{\pm}$p and $\pi^{\pm}$d scattering [Particle Data Group, 2006].

2 Total cross sections at the Brookhaven 33 GeV AGS

At BNL a series of measurements were made with different beams covering the resonance region and the beginning of the continuum region, 0.5< p_{lab} <22 GeV/c [1, 2, 3].

A precise total cross section measurement in the resonance region was then a method to detect new resonances and this was the main aim of the Brookhaven measurements. Low mass resonances are easy to detect because they produce large effects. Higher mass resonances show up as broad and non prominent structures, often overlapping with one another, so that one needs to measure the total cross sections with high precision at many closely spaced points. Errors in the absolute values can be tolerated if they are essentially energy independent.

The π^+p, K^+p, and pp are pure isospin states. In the other cases one has a mixture of two isospin states. The determination of the pure isospin cross sections requires the measurement of two cross sections, which involves changing either the incident or the target particle. For pions it is easy to measure both π^+p and π^-p cross sections, and hence to derive the total cross sections $\sigma_{1/2}$ and $\sigma_{3/2}$ for pure isospin states. For the other cases the simplest solution is to measure the cross sections off protons and off neutrons. The best neutron target is a bound neutron-proton state (the deuteron): problems of nuclear physics in the deuteron limit the analysis of the data and an unfolding procedure must be performed to extract the pure isospin cross sections.

Total cross section measurements do not provide enough information to establish conclusively that a peak in a definite isospin state is a resonant state, i.e. a state with definite quantum numbers. In fact, a structure could also come from a threshold effect, such as the opening up of a new important channel, or other kinematical effects.

The method employed was that of a standard transmission "good geometry" experiment. The used low energy beams were partially separated secondary beams. After momentum and mass separation, the beam was defined by a sysytem of scintillation counters and by a Cherenkov counter, which electronically distinguishes between wanted and unwanted particles. The beam alternatively passed through a hydrogen, deuterium, or dummy target and converged to a focus at the location of the transmission counters, each of which subtended a different solid angle from the center of the target. This allowed to evaluate the partial cross sections σ_i measured by each individual transmission counter and to extrapolate these cross sections to zero solid angle to obtain the total cross section.

In the K^+N, I=0 state there is a structure at the center of mass (c.m.) energy of about 1910 MeV. Many measurements were made on this system, without reaching a final conclusion, though a possible I=0 resonant state seemed to be indicated for this "exotic system" [4]. The K^+p system received considerable attention few years ago, with the possible observation of a narrow "pentaquark state". This possibility seems now to be disfavoured [5].

3 Total Cross Sections at the IHEP 70 Gev protonsynchrotron

The program of the first CERN-IHEP (Serpukhov) Collaboration concerned the measurement of the energy dependence, first in 1969 of the π^-p, K^-p and $\bar{p}p$ total cross sections and later, in 1971, of the K^+p, π^+p and pp total cross sections in the lab momentum range 15-60 GeV/c [6, 7]. The experimental method was similar to that used in Brookhaven, that is a standard transmission method in good geometry, using more refined Cherenkov counters (see the similar layout used at Fermilab, Fig. 3)

The 1969 results from the first set of measurements with negative particles (π^-, K^-, $\bar{p}$) indicated that the decrease of the three measured cross sections almost stopped, leading to essentially energy independent total cross sections, Figs. 1, 4. The results from the second (1971) set of measurements using positive particles (p^+, K^+, p) in the same momentum range lead to similar conclusions for π^+p and pp, Figs. 1, 4, and to the surprising discovery of rising K^+p, K^+d total cross sections, Figs. 1, 2, 4. This came as a surprise to most physicists[1], even if some theoreticians had predicted a possible rise [8]. Fig. 2 shows the rising K^+p total cross section at increasing energies measured at Serpukhov; the same features were observed in the K^+d and K^+n cross sections. The π^+p and pp data were instead found to be almost energy independent, suggesting that they had a minimum at these energies, Fig. 2, 4. Moreover $\sigma_{tot}(pp) \simeq \sigma_{tot}(pn)$ in agreement with isospin independence. The comparison of the total

[1]Personal recollection. At the beginning of 1970 a group of CERN physicists involved in the first CERN-Serpukhov experiment, before leaving for a new run period at Serpukhov, had a coffee discussion in the CERN canteen. They were joined by several friends. The discussion concerned the expected asymptotic energy behaviour of the total hadron-hadron cross sections: most experimentalists favoured constant, energy independent cross sections, while most theoreticians favoured decreasing cross sections going towards zero. In the middle of the discussion arrived Giuseppe Cocconi, the CERN "father" of these types of measurements: he listened for a while, then he "exploded": "It is all nonsense: I bet a coffee that the cross sections will rise!" This proposal sounded a bit crazy, so I and others accepted the bet... and a couple of years later, at the beginning of 1972, Cocconi wanted the free coffee!

cross sections for particles and antiparticles on protons indicated that their differences were decreasing with increasing energies. This was particulary evident when plotting the total cross section differences:

$$\Delta\sigma = \sigma_{tot}(\bar{x}p) - \sigma_{tot}(xp) = A\ p_{lab}^{-n} \tag{1}$$

The behaviour is consistent with the Pomeranchuck theorem according to which $\Delta\sigma \to 0$ as $p \to \infty$ [9].

The study of charged hadron production vs lab momentum was also an important point, as indicated in ref. [10, 11]. Also the measurements of the absorption cross sections in various nuclei was a relevant point [12].

In the subsequent years there were cosmic ray experiments which indicated a possible increase of $\sigma_{tot}(pp)$ at the highest Cosmic Ray (CR) energies [13].

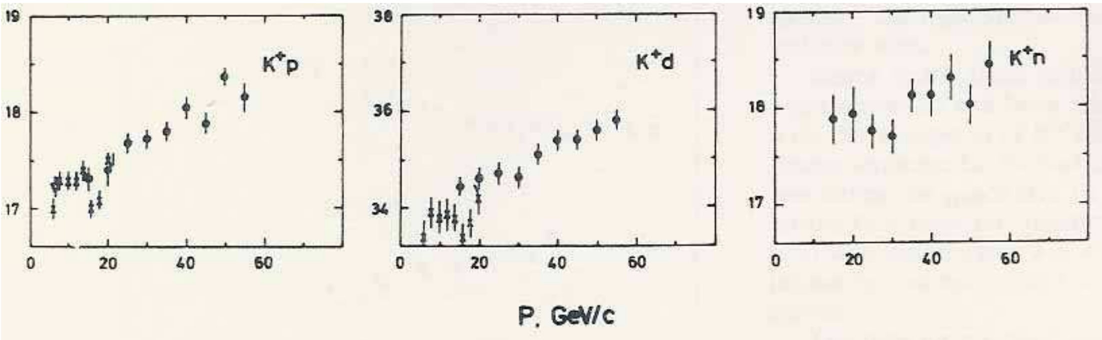

Figure 2: The rising K$^+$p, K$^+$d and K$^+$n total cross sections measured at Serpukhov by the CERN Serpukhov Collaboration [7]

4 Total Cross Sections at the CERN-ISR

The CERN Intersecting Storage Rings (ISR) consisted of two concentric and slightly distorted rings for protons, each 300 m in diameter. The two rings intersected horizontally eight times, with a crossing angle of 14.8°. The ISR operated at c.m. energies $\sqrt{s} = 23.4$, 30.4, 44.4, 52.6 and 62.3 GeV [14, 15, 16]. A key parameter of the ISR was the luminosity L, which determined the total number of interactions per unit time, R, in each intersection

$$R = L\sigma_{tot}(pp) \tag{2}$$

where $\sigma_{tot}(pp)$ is the cross section at each energy. The luminosity was measured by the Van der Meer method of displacing the two beams vertically from one another, recording the rate R in a monitor [14, 15, 16].

The direct method for the measurement of the pp total cross section at the ISR was based on the application of the luminosity formula, Eq. 2, performing separate measurements of R and L. The total number of interactions was measured with large scintillation counters; extrapolations had to be made to take into account the missing number of interactions, mainly at small angles. L was measured as stated above.

Indirect methods for the measurement of $\sigma_{tot}(pp)$ were connected with the use of the optical thorem

$$lm\ F(s,0) = s\ \sigma_{tot}(s) \tag{3}$$

Squaring expression (3) leads to a relation between the square of the total cross section and the elastic differential cross section at t=0

$$\sigma_{tot}^2 = 16\pi(\hbar c)^2(dN_{el}/dt)|_{t=0}/L(1+\rho^2) \tag{4}$$

where $(\rho = ReF/lmF)|_{t=0}$ is the ratio at t=0. The differential elastic cross section is written as

$$dN_{el}/dt = |dN_{el}/dt|_{t=0}\ exp(-B|t|) \tag{5}$$

Another expression for the total cross section is

$$\sigma_{tot} = (N_{el} + N_{inel})/L \tag{6}$$

N_{el} and N_{inel} were measured simultaneously. Three indirect methods where used at the ISR.

The first method used the measurement of the elastic cross section at small angles, extrapolating it to t=0 by means of Eq. 3, then using Eq. 4 with a measurement of the luminosity L, and an estimate for $\rho = ReF/ImF$, assumed to be t-independent.

The second method was based on the measurement of the elastic scattering cross sections in the Coulomb-Nuclear interference region, for $0.001 < |t| < 0.01$ (GeV/c)^2. In this region the expression for the cross section depends on the high energy parameters ρ, B, σ_{tot}. Several types of fits were performed, for example leaving both ρ and σ_{tot} as free parameters. In this case one has an absolute normalization to the Coulomb scattering formula, which is well calculable.

The third method was based on the simultaneous measurements of the total collision rate and of elastic scattering in the nuclear region, then using Eq. 3: the measurement of σ_{tot} does not depend on the luminosity, thus removing one of the uncertainties.

All measurements indicated the $\sigma_{tot}(pp)$ was rising with increasing energies, see Fig. 4.

5 Total Cross Sections at the Fermilab fix target accelerator

Fig. 3 shows the layout of the total cross section measurements at the Fermilab fix target accelerator (separated function synchrotron operating at 300 and at 400 GeV). The differences compared to previous measurements were due to the higher energies of the Fermilab beams, thus to the need of more selective differential Cherenkov counters. Incident particles were defined by scintillation counters and identified by two differential gas Cherenkov counters, allowing cross sections of two different particles to be measured simultaneously. In addition, a threshold gas Cherenkov counter could be used in anticoincidence. Sufficient $\pi^+ - K^+$ separation was achieved up to 200 GeV/c, and at higher momenta using corrected optics [17]. Contamination of unwanted particles in the selected beam particles was <0.1%. In the pion and kaon beams there were small admixtures of muons and electrons (at the level of 0.1% and 1%, respectively). Electrons were identified by their characteristic signal in a 22-radiation length lead-glass Cherenkov counter placed downstream of the transmission counters. Muons were identified by their ability to pass through 5 m of steel placed downstream of the transmission counters. Other differences concerned the order in the transmission counters (first the large transmission counters at Brookhaven, and the reverse at Fermilab). The transmission counters could be moved on rails so as to subtend at each energy the same t-range. The data were taken first in the range 50 to 200 GeV/c secondary beam momentum, and later in the ranges 23-280 and 200-370 GeV/c.

A compilation of all measured data is given in Fig. 4a. These measurements reveal that the total cross sections and thus the effective sizes of both the proton and neutron increase for five of the six probes when their lab energy increases. For the sixth, the antiproton, the rapid decrease previously observed below 50 GeV/c had slowed down and the apparent size becomes essentially constant above 120 GeV/c.

The similarities of the behaviour of the cross sections with the six probing particle beams indicate that a new simplicity of nature was revealing itself at high energies. All of the particle-proton and

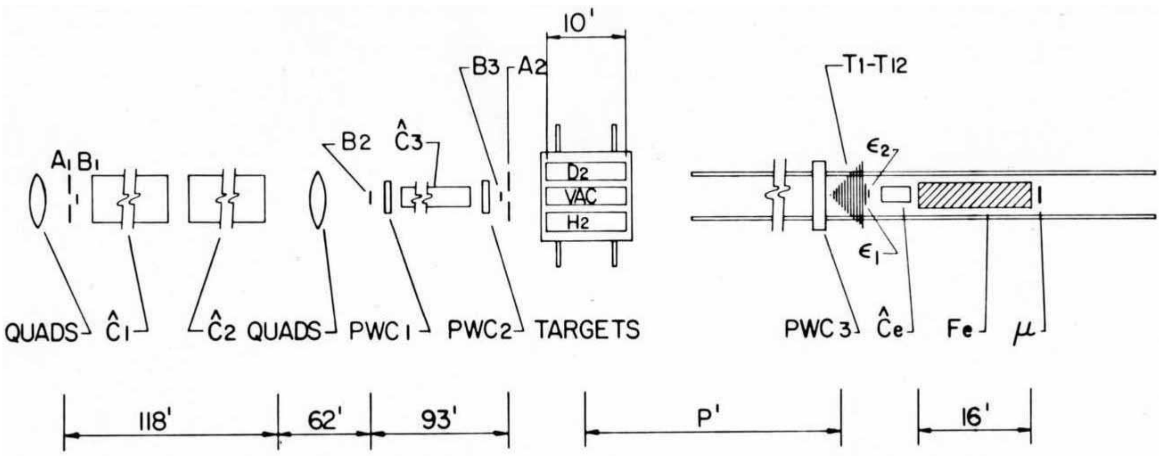

Figure 3: Layout of the apparatus for the measurement of the charged hadron total cross sections at Fermilab. C_1, C_2 ,C_3 are gas differential (threshold) Cherenkov counters, PWC1-PWC3 are proportional wire chambers B_1-B_3 and A_1-A_2 are scintillation counters. H_2, D_2, VAC are the liquid hydrogen liquid deuterium and dummy targets, T_1-T_{12} are transmission counters, ϵ_1-ϵ_2 are small scintillation counters used for efficiency measurements, C_e is a lead glass Cherenkov counter; the iron absorber and the muon (μ) scintillation counter were used to estimate the muon contamination. The beam was counted as $B = B_{123}\ \bar{A}_{12}\ C_i$, where C_i was a combination of the 3 Cherenkov counters.

antiparticle-proton cross section pairs uniformly approach each other, see Figs. 4, 5. For each probe particle, the neutron cross section is nearly equal to the proton cross section. The differences between particle and antiparticle pairs seems to be disappearing at very high energies.

As already stated, the study of total cross sections requires first a study of the beam qualities and of their fluxes; this provides interesting information on the production cross sections of the six long lived charged hadrons, see Fig. 6 [10]. Besides the liquid hydrogen, deuterium and dummy targets, one had always available a number of targets of different materials (Li, C, Al, Cu, Sn and Pb). Thus one had the possibility of measuring the absorption cross sections in nuclei [12].

The multiplicity of charged particles produced in inelastic processes was measured in several experiments and was found to be increasing with energy [18].

6 Total cross sections at the CERN and Fermilab $\bar{p}p$ colliders

The logical continuation of the total cross section measurements performed at the fixed target BNL, Serpukhov and Fermilab accelerators and at the CERN ISR pp collider was to measure the total antiproton-proton cross section at the CERN [19, 20] and Fermilab [21, 22, 23] $\bar{p}p$ colliders, up to 1.8 TeV c.m. energy. A few members of the previous collaborations measured the antiproton-proton total and elastic cross sections at CERN and Fermilab. The CERN $\bar{p}p$ collider used a modified SPS, while the Fermilab collider used the superconducting ring. As already discussed for the CERN-ISR, at a $\bar{p}p$ collider, one needs a layout considerably different from the transmission measurements performed at fixed target accelerators. In order to measure elastic scattering at very small angles, precise detectors had to be positioned very far from the collision point (~100 m at Fermilab) inside containers (the so called "Roman pots") placed very close (few mm) from the circulating beams.

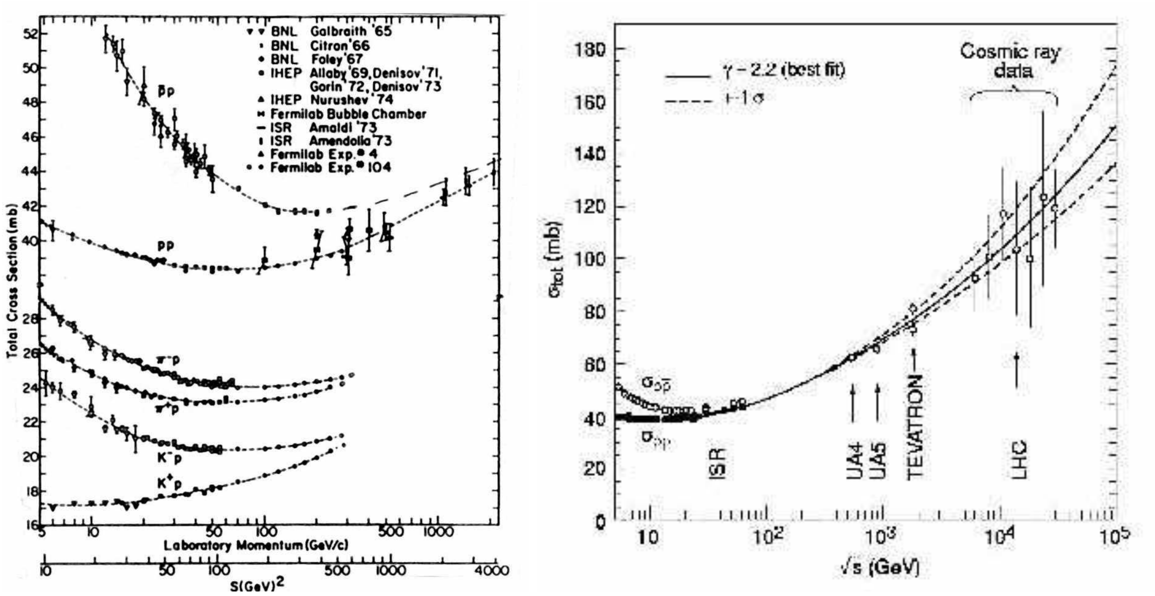

Figure 4: (a) Compilation of $\bar{p}p$, pp, π^-p, π^+p, K^-p, K^+p total cross sections plotted versus c.m. energy. (b) The $\bar{p}p$ and the pp total cross sections, including cosmic ray measurements. The solid line is a fit of the σ_{tot} and ρ data with dispersion relations; the region of uncertainty is delimited by dashed lines.

Since the circulating p and $\bar{p}$ were inside the same ring, one could not use the Van der Meer method for measuring the luminosity: L is here known to a considerably smaller precision. Thus the luminosity independent method is more precise.

Both the CERN and the Fermilab collider results established that the antiproton-proton total cross sections increase with increasing c.m. energies, Fig. 4b. The same experiments allowed to measure the high energy parameters: the total cross section σ_{tot}, the elastic cross section σ_{el}, the ratio σ_{el}/σ_{tot}, the parameter $\rho_{t=0}$, the slope B of the elastic nuclear differential cross section [24].

7 *pp* total cross sections from cosmic rays

The cosmic ray *pp* total cross sections shown in Fig. 4b were obtained in a rather indirect way. Cosmic ray exstensive air showers (EAS) measure the electromagnetic showers originated by p-air interactions yielding π^0 production followed by $\pi^0 \to 2\gamma$ decay. EASs measure the attenuation Λ of the rate of showers at different depths in the atmosphere. From this, the p-inelastic cross section may be obtained. A series of Monte Carlo simulations allow to correlate primary cosmic ray energy spectra, to interactions in air, electromagnetic showers, Λ and σ_{inel}^{p-air}. Other MCs correlate σ_{inel}^{p-air} with σ_{tot}^{pp}, usually assuming the Glauber theory of p-air interactions [25, 26].

The results have large statistical and systematic uncertainties. But nevertheless the data are in good agreement with increasing *pp* total cross sections [13].

Analyses of the global $\bar{p}p$ and *pp* data (measured by the Serpukhov, E104, ISR, UA4, UA5, CDF, E710, E811, cosmic ray experiments) using Regge pole formulae yield the following value for the *pp* total cross section at the LHC: $\sigma_{tot}^{pp}(\sqrt{s} = 14\ TeV) \sim 108$ mb [26] [27].

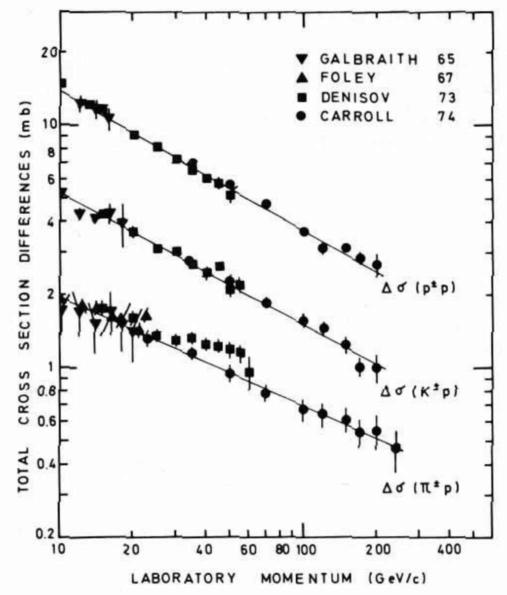

Figure 5: The differences of total cross sections for $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ interactions with protons. The solid lines represent fits of the data to a power law dependence.

George Zatsepin was a pioneer in this field: he was a theoretician, a phenomenologist and performed experiments. He discussed the famous GZK cut off in the cosmic ray primary flux at $\sim 3 \cdot 10^{19}$ eV due to the interactions of the highest energy cosmic rays with the cosmic microwaves background radiation at 2.7 K. He determined several analytic formulae and he was the first to establish the chain:
CR spectrum $\rightarrow$ CR interactions with the atmosphere $\rightarrow$ production of $\pi^{\pm}$, π^0, K $\rightarrow$ $\pi^{\pm}$, π^0, K decays $\rightarrow$ EASs $\rightarrow \Lambda \rightarrow \sigma_{tot}$ ... [28].

8 Conclusions. Perspectives

In 1971 the experiment at the Serpukhov accelerator revealed that the K^+p total cross section increased with energy. In 1972 were published the first CR indications for rising pp total cross sections. In 1973 the increase of the pp total cross section was observed at the CERN ISR. Later in 1974-1978 the rising of $\pi^{\pm}$p, K^-p cross sections was observed at the Fermilab fix target accelerator and finally the rising $\bar{p}p$ was measured at the CERN and Fermilab $\bar{p}p$ colliders. We now know that at very high energies all total hadron-hadron cross sections increase with energy; this was confirmed, even if with lower precision, by the highest energy cosmic ray data. (Also the γp total cross sections increase with energy).

From a theoretical point of view we still cannot obtain from the QCD lagrangian the answer to the question of why all the hadronic total cross sections grow with energy. In many QCD inspired models the rise may be connected with the increase of the number of minijets and thus to semi-hard gluon interactions. At the same time it is more or less clear that the rise of the total cross sections is just the shadow of particle production: through the optical theorem the total cross section is related to the imaginary part of the elastic scattering amplitude in the forward direction.

The high energy elastic and total cross section data vs energy have been usually analized in terms of

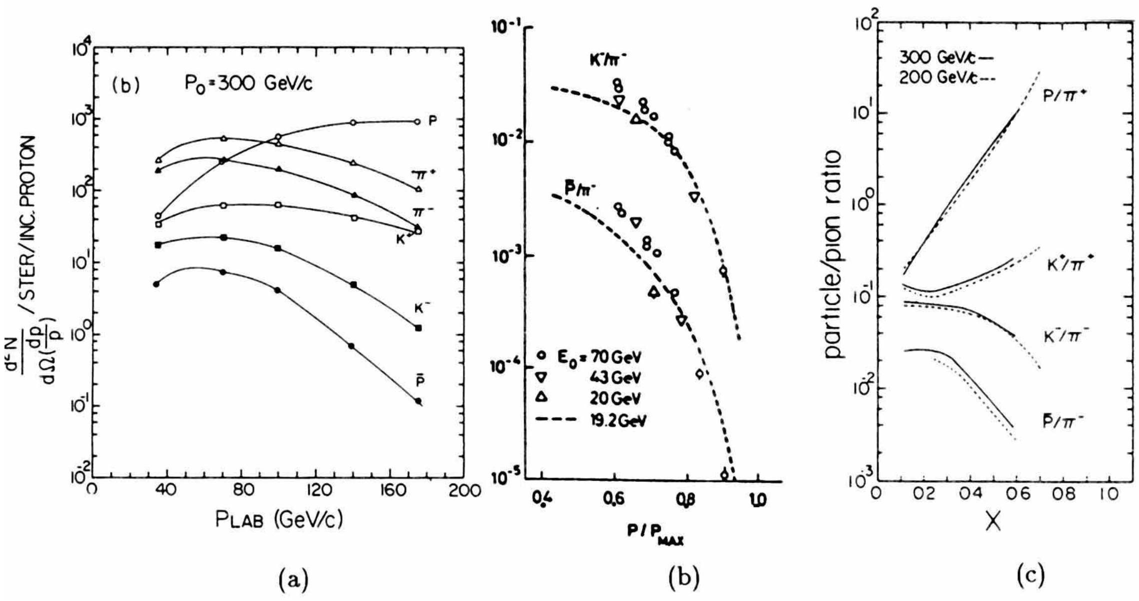

Figure 6: (a) Production cross sections of the six long-lived charged hadrons plotted vs lab momentum (incident proton beam p_{lab} = 300 GeV/c); (b) (c)particle ratios vs p/p_{max} at p_{lab}= 70 GeV at Serpukhov.

Regge Poles, and thus in terms of Pomeron exchange. Even if the Pomeron was introduced long time ago we do not have a consensus on its exact definition and on its detailed substructure. Some authors view it as a "gluon ladder". From these fits were obtained predictions for the pp total cross section at the LHC.

Future experiments on hadron-hadron total cross sections will rely on the RHIC collider at BNL and mainly on the LHC proton-proton collider at CERN.

Large area cosmic ray experiments may be able to improve the data in the ultra high energy region and solve some of the open problems, in particular the GZK cut off.

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